REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
FINAL REPORT

3. DATES COVERED *(From - To)*
01 FEB 2004 - 30 JUN 2007

4. TITLE AND SUBTITLE
STUDIES WITH LASER COOLED ATOMS AND SINGLE MOLECULES

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-04-1-0040

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
PROFESSOR CHU

5d. PROJECT NUMBER
2301/DX

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
STANFORD UNIVERSITY
651 SERRA STREET SUITE 220
STANFORD CA 94305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF OFFICE OF SCIENTIFIC RESEARCH
875 NORTH RANDOLPH STREET ROOM 3112
ARLINGTON VA 22203
DR ANNE MATSUURA

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMEN A: UNLIMITED

AFRL-SR-AR-TR-07-0443

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have achieved milestones in atom interferometry. By using multiphoton Bragg diffraction to make beam splitters that transfer the momentum of up to 24 photons to the atoms, we are able to increase the signal by a factor of 12 for Mach-Zehnder or 144 for Ramsey-Borde Interferometers relative to the 2-photon beam splitters used in the best present interferometers. We are also able to run Ramsey-Borde interferometers simultaneously to suppress the influence of vibrations. Work continues to make the experimental setup reliable, as required for routine data taking and tracking down systematic effects at the 0.1 parts per billon level of precision.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Progress Report
Studies with Laser Cooled Atoms and Single Molecules
Award Number FA9550-04-1-0040

02/04 to 09/07

Steven Chu, Principle Investigator
Stanford University
651 Serra Street
Stanford, CA 94305-6215
(650)723-9102

I. Summary of Progress

A) Atom Interferometry

We have achieved milestones in atom interferometry. By using multiphoton Bragg diffraction to make beam splitters that transfer the momentum of up to 24 photons to the atoms, we are able to increase the signal by a factor of 12 for Mach-Zehnder or 144 for Ramsey-Borde Interferometers relative to the 2-photon beam splitters used in the best present interferometers. We are also able to run Ramsey-Borde interferometers simultaneously to suppress the influence of vibrations.

Work continues to make the experimental setup reliable, as required for routine data taking and tracking down systematic effects at the 0.1 parts per billon level of precision.

B) New States of Matter and Nonlinear Atom Optics

Progress was made in investigating fractional quantum-Hall like effects in the centrifugal limit of small, rotating Bose gasses. An ensemble of such gases is prepared in an optical lattice with locally rotating lattice site potentials. The non-rotating ground states are adiabatically transformed to higher angular momentum states by applying a controlled quadrupole deformation of the rotating lattice potential. Near the centrifugal limit, where the trap rotates near its vibration frequency, reduction in atom-atom correlation is expected as a result of interatomic collisions. The onset of this behavior is probed with laser-induced (photoassociative) transitions to bound molecules. Experimental data shows a suppressed photoassociation response near the centrifugal limit. Current work is directed toward determining whether this effect is the result of atomic correlation or modifications to local density.

Effects of nonlinear atom optics were investigated with superfluid Bose-Einstein condensates in periodically modulated optical lattices. Parametric amplification of matter waves was observed under appropriate phase-matching conditions, which were achieved with new techniques based on band-shaping effects in periodically translated optical lattices.

C) Polymer Dynamics with Single Molecules

We have developed a technique to construct DNA brushes by immobilizing multiple λ-DNA labeled streptavidin coated beads on the substrate. We have achieved a grafting density of 25 DNA/R_g^2. Taking advantage of the excellent spatial resolution of the confocal microscope, the parabolic monomer density profile along the swelling direction of the polymer brush, which was proposed by S.T. Milner in 1988, has been demonstrated. At the single molecule level, in addition to the high frequency thermal motion around the DNA backbone, longer time scale collective modes, which were first proposed by de Gennes in 1987, were also observed. The escape of a swelling molecule from the brush region to the random coil state in the buffer region was also monitored.

We also presented the direct visualizations of single, entangled DNA polymers in three flow experiments: relaxation following a rapid shear deformation, steady shear, and startup shear. The four concentrations studied displayed similar rheological features to synthetic polymers at comparable concentrations and were accordingly classified from semidilute to well-entangled. In entangled solutions, we uncovered two distinct relaxation time scales, with the fast, chain retraction characteristic time, tau(fast) approximate to 10-fold longer than the rotational Rouse time assumed by theoretical models. We also found a high degree of molecular individualism and broad conformational distributions in all experiments at shear rates (gamma) over dot > tau(-1)(fast). This new evidence restricts the applicability of the pre-averaging approximation underlying all closed-form theories developed to date and explains some of the complications in modeling nonlinear flows.

D) Biophysics

We have developed a simple method to bond optical components using silica nanoparticle sol-gel chemistry. The silica nanoparticles polymerize into highly branched networks that link the surfaces together. The nanoparticle mediated bonding has several advantages to currently used optical joining technologies. The bonding is a room temperature process and does not require any clean room facilities. The bonded interface has a high mechanical strength and low scattering. The bonding is resistant to organic solvents on silylation with hydrophobic surface groups. This method achieves 100% successful bonding rates between soda lime glass slides. The bond-setting time can be tailored to allow time for precision optical alignment.

We also extended our previous single molecule studies of ribosome. The detailed mechanism of how the ribosome decodes protein sequence information with an abnormally high accuracy, after forty years of study, remains elusive. A critical element in selecting correct tRNA transferring correct amino acid is "induced fit" between the ribosome and tRNA. Using single molecule methods, the induced fit mechanism is shown to favorably position the correct tRNA after initial codon recognition. We provide evidence that this difference in positioning and thermal fluctuations constitutes the *primary* mechanism for the initial selection of tRNA. This work demonstrates thermal fluctuations playing a critical role in the substrate selection by an enzyme

II. Personnel

The following personnel were supported by or associated with projects supported by this funding:

Post-Doctoral Researchers: Dr. Holger Müller, Dr. Quan Long, Dr. Yannick Bidel, and Dr. Wen-Tau Juan

Graduate Students: Sheng-wey Chiow, Seokchan Hong, Edina Sarajlic, Nathan Gemelke, Rodrigo Teixeria

In this period, Seokchan Hong, Rodrigo Teixeria, Nate Gemelke completed their work and earned PhDs. Nate is currently holds the Grainger Postdoctoral Fellowship in the Physics Department at the University of Chicago. Rodrigo is a research scientist at Computational Medicine and Biology (CMB) Div. of CFD Research Corporation. Seokchan Hong is senior engineer at Samsung Electronics Co., Ltd. in Korea. My expectation is that Sheng-wey Chiow and Edina Sarajlic will defend their thesis within 6 months.

Yannick Bidel and Wen-Tau Juan have returned to their home countries. Yannick is a research engineer at ONERA, France, and Wen-Tau is a research fellow at the Academia Sinica in Taiwan. Holger Müller is the lead postdoctoral fellow in my group and is applying for Assistant Professor jobs at U. of Chicago, Princeton, UC Berkeley and other institutions. Dr. Quan Long is assistant professor of physics at Huazhong University, China.

III. Accomplishments and New Findings

Atom Interferometry

Multiphoton- and simultaneous conjugate Ramsey-Borde atom interferometers, Holger Müller, Sheng-wey Chiow, S. Herrmann, and S. Chu, Proc. 3rd Mexican Meeting on Mathematical and Experimental Physics, to appear in AIP Conf. Proc. (2007).

Beyond the status reported in the article below, we have meanwhile accomplished the aim of running two conjugate Ramsey-Borde interferometers simultaneously. They are based on high-order Bragg diffraction transferring (at present) up to 18 photon recoils. Thereby, we can increase the useful pulse separation time tenfold to about 30ms. The influences limiting this are currently being studied. It is hoped that with Raman sideband cooling and improved wavefront quality of the Bragg beams, it can be increased to 400ms, which would then be limited by the height of the vacuum chamber. A first report on this will appear in this conference proceedings.

Atom Interferometry with up to 24-Photon-Momentum-Transfer Beam Splitters, Holger Müller, Sheng-wey Chiow, Quan Long, Sven Herrmann, and Steven Chu, submitted to Science (2007)

Valuable tools for precision measurements, atom interferometers split and reflect matter waves by light pulses, which change the internal quantum state of the atom and transfer the momentum of a pair of photons. We use multiphoton Bragg diffraction to transfer the momentum of up to 12 photon pairs in a single process to increase the phase shift by factors of 12 for Mach-Zehnder or 144 for Ramsey-Borde geometries. Moreover, Bragg diffraction does not change the atom's internal state, which enables a cancellation of important systematic effects. This dramatic increase in sensitivity and precision due to large-momentum transfer beam splitters opens the door to improved measurements of the fine-structure constant, of inertial forces, and tests of fundamental theories such as relativity or quantum electrodynamics.

Atom-light interactions can be used to split, reflect and recombine matter waves to form light-pulse atom interferometers. These are excellent tools for precision measurements. For example, a phase shift of $2nkgT$ in Mach-Zehnder (MZ-) interferometers depends on the gravitational acceleration g, the pulse separation time T, and the momentum $2n\hbar k$ transferred by the pulses, where k is the wavenumber of the light and n an integer. Among other applications, MZ interferometers have been used to measure g and its gradient, the Sagnac effect, and Newton's gravitational constant with sensitivities that compare favorably with other state-of-the-art instruments. Moreover, they are hoped to provide us with one of the best tests of the equivalence principle. In Ramsey-Borde (RB-) interferometers, an additional phase shift $\varphi_r = 8\omega_r n^2 T$, where $\omega_r = \hbar k^2/(2M)$ is the recoil frequency of Cesium atoms and M their mass, arises due to the recoil of the atom when scattering $2n$ photons per beam splitter. This allows a measurement of $\hbar / M$; in combination with the Rydberg constant R_∞ and the Cs to electron mass ratio M / m_e, which are known to precisions of 0.008 and 0.5 ppb, respectively, this provides us with one of the best measurements of the fine-structure constant

$$\alpha^2 = \frac{2R_\infty}{c}\frac{M}{m_e}\frac{h}{M}.$$

Further progress is hoped to reach the sub-ppb level of precision.

In previous interferometers, the beam splitters are often 2-photon Raman transitions between hyperfine ground states, so that n=1. As the phase shift due to gravity is proportional to n and the one due to the recoil even proportional to n^2, it is obviously desirable to increase n. In this work, we significantly extend the potential of large momentum transfer in light pulse interferometry. We report the highest momentum transfer of $30\hbar k$ achieved with Bragg diffraction and atom interferometry in both MZ and RB geometries with up to $24\hbar k$ beam splitters. This includes the first RB interferometer with n>1 and the largest momentum transfer in the beam splitters of any light-pulse atom interferometer. For measuring h/M, we thus realize the quadratic signal increase relative to Raman transitions; in our case, 144-fold. Moreover, even with high $12\hbar k$ momentum transfer, we achieve an excellent visibility of 52% in Mach-Zehnder and 36% in Ramsey Borde geometry (where the theoretical maximum is 50%). We observe contrast up to a pulse separation of 100ms.

Factors that lead to this progress include (i) an atomic fountain, which leads to more accurate control of the photon-atom interactions in terms of timing and intensity than atomic beam setups (ii) a 6-W injection locked Ti:sapphire laser system for generating intense Bragg beams (iii) good wavefront quality and large diameter of the Bragg beams (which also helps to reduce systematic effects in precision measurements) (iv) a secondary phase locked loop to reduce phase noise. We expect to increase the pulse separation to up to 0.4s, limited by the 1-m length of the vacuum tube, by Raman sideband cooling of the atoms to limit their thermal radial spread and by use of simultaneous conjugate interferometers to cancel the influence of vibrations. This, together with the up to 144-fold signal increase demonstrated in this work, the low phase noise of our laser system, and the reduction in systematic effects (notably the Zeeman and Stark effect) offered by Bragg diffraction, opens the door to substantial improvements in measurements of the recoil frequency and the fine-structure constant and others. The potential of multiphoton Bragg diffraction for this and other future atom interferometers is clear.

Atom Interferometry tests of the isotropy of post-Newtonian gravity, Holger Müller, Sheng-wey Chiow, Sven Herrmann, Steven Chu, Keng-Yeow Chung, submitted to Phys. Rev. Lett. (2007).
Atom Interferometry tests the isotropy of post-Newtonian gravity, H. Müller, S.-w. Chiow, S. Herrmann, S. Chu, and K.-Y. Chung, in preparation for A. Kostelecky (ed.), CPT and Lorentz Symmetry III, World Scientific, Singapore (2007).

In this letter, we report three types of results: First, a gravimeter based on cold atoms, which uses a pulse separation of 0.4s and a bright source of Cs atoms using Raman sideband cooling in an optical lattice. It reaches a resolution of $8\times10^{-9}g/\sqrt{\text{Hz}}$. This is the highest resolution reported for any cold atom gravimeter thus far. Second, we analyze the expected modulation of the local gravitational acceleration apparent in this experiment as a result of Lorentz violation in both post-Newtonian gravity and electromagnetism. That these relevant influences are both understood theoretically makes tests of Lorentz symmetry based on atom interferometry particularly clean. Having developed this interferometer and the underlying theory, we test the local Lorentz invariance of post-Newtonian gravity by monitoring Earth's gravity and comparing the observed modulations with a Newtonian model based on the relative distances of the Earth, the Moon, the Sun, and the planets. Expressed within the standard model extension (SME) or Nordtvedt's anisotropic universe model, the analysis limits four coefficients describing anisotropic gravity at the ppb level and three others, for the first time, at the 10ppm level. Using the SME we explicitly demonstrate how the experiment actually compares the isotropy of gravity and electromagnetism.

Quantum Physics Exploring the Outer Solar System: The SAGAS Project, P. Wolf, A. Clairon, L. Duchayne, A. Landragin, P. Lemonde, G. Santarelli, W. Ertmer, E. Rasel, G.M. Tino, P. Gill, H. Klein, S. Reynaud, C. Salomon, E. Peik, O. Bertolami, P. Gil, J. Pamos, A. Rathke, C. Jentsch, P. Bouyer, D. Izzo, L. Cacciapuoti, P. De Natale, P. Touboul, B. Christophe, S.G. Turyshev, J.D. Anderson, M.E. Tobar, F. Schmidt-Kaler, J. Vigue, L. Marmet, M-C. Angonin, P. Delva, P. Tourrenc, G. Metris, Holger Müller, and R. Walsworth, arXiv:0711.0304 (2007).

This article describes the SAGAS deep space mission that is proposed for the European space agency's cosmic vision program. The mission is proposed mainly as a study of gravitational forces in the outer solar system to probe the anomalous acceleration observed in the Pioneer 10 and 11 probes. The proposed satellite carries a cold atom accelerometer to monitor any residual acceleration relative to an inertial frame and a microwave as well as laser downlink for accurate ranging.

Nanosecond electro-optical switching with a repetition rate above 20,MHz, Holger Müller, Sheng-wey Chiow, Sven Herrmann, and Steven Chu, Rev. Sci. Instr., in press (2007).

We describe an electro-optical switch based on a commercial electro-optic modulator (modified for high-speed operation) and a 340V pulser having a rise time of 2.2ns (at 250V). It can produce arbitrary pulse patterns with an average repetition rate beyond 20MHz. It uses a grounded-grid triode driven by transmitting power transistors. We discuss variations that enable analog operation, use the step-recovery effect in bipolar transistors, or offer other combinations of output voltage, size, and cost. This switch enables a new variant of fluorescence detection of atoms, as the fluorescence can be detected after coherently transfer the population in the excited state. Thus, detection happens when the driving laser beam is off, so that no stray light reaches the detector. A high repetition rate enables a substantial number of photons per atom to be detected, so that atom-shot-noise limited detection is feasible.

Relativity tests by complementary rotating Michelson-Morley experiments, Holger Müller, Paul Louis Stanwix, Michael Edmund Tobar, Eugene Ivanov, Peter Wolf, Sven Herrmann, Alexander Senger, Evgeny Kovalchuk, and Achim Peters, Phys. Rev. Lett. **88,** 050401 (2007).

We report Relativity tests based on data from two simultaneous Michelson-Morley experiments, spanning a period of more than one year. Both were actively rotated on turntables. One (in Berlin, Germany) uses optical Fabry-Perot resonators made of fused silica; the other (in Perth, Australia) uses microwave whispering-gallery sapphire resonators. Within the standard model extension, we obtain simultaneous limits on Lorentz violation for electrons (5 coefficients) and photons (8) at levels down to 10^{-16}, improved by factors between 3 and 50 compared to previous work.

Limits to differences in active and passive charges, C. Lämmerzahl, A. Macias, and H. Müller, Phys. Rev. A **75,** 052104 (2007).

We explore consequences of a hypothetical difference between active charges, which generate electric fields, and passive charges, which respond to them. A confrontation to experiments using atoms, molecules, or macroscopic matter yields limits on their fractional difference at levels down to 10^{-21}, which at the same time corresponds to an experimental confirmation of Newtons third law.

Extended-cavity diode lasers with tracked resonances, Sheng-wey Chiow, Quan Long, Christoph Vo, Holger Müller, Steven Chu, *accepted for Applied Optics* (2007).

We increase the reliability of long-term mode hop free operation of grating-stabilized diode lasers by feeding back a direct current to the diode which is determined such that it minimizes the amplitude or frequency noise of the laser. This keeps the laser running in the middle of a stable region of the mode chart, even if these drift due to external influences such as temperature variations. We achieve 12 days of continuous mode-hop free operation, after which the laser was deliberately turned off.

Diffraction between the Raman-Nath and the Bragg regime: Effective Rabi frequency, losses, and phase shifts, Holger Müller, Sheng-wey Chiow, and Steven Chu, arxiv: 0704.2627, submitted to PRA (2007)

We present an analytic theory of the diffraction of (matter) waves by a lattice in the ``quasi-Bragg" regime, by which we mean the transition region between the long-interaction Bragg and ``channelling" regimes and the short-interaction Raman-Nath regime. The Schrödinger equation is solved by *adiabatic expansion,* using the conventional adiabatic approximation as a starting point, and re-inserting the result into the Schrödinger equation to yield a second order correction. Closed expressions for arbitrary pulse shapes and diffraction orders are obtained and the losses of the population to output states otherwise forbidden by the Bragg condition are derived. We consider the phase shift due to couplings of the desired output to these states that depends on the interaction strength and duration and show how these can be kept negligible by a choice of smooth (e.g., Gaussian) envelope functions even in situations that substantially violate the adiabaticity condition. We also give an efficient method for calculating the effective Rabi frequency (which is related to the eigenvalues of Mathieu functions) in the quasi-Bragg regime.

A new photon recoil experiment: towards a determination of the fine structure Constant, Holger Müller, Sheng-wey Chiow, Quan Long, Christoph Vo, and Steven Chu, Appl. Phys. B. **84**, 633 (2006)

We report on progress towards a measurement of the fine structure constant α to an accuracy of 5×10^{-10} or better by measuring the ratio h/m_{Cs} of the Planck constant h to the mass of the cesium atom m_{Cs}. Compared to similar experiments, ours is improved in three significant ways: (i) simultaneous conjugate interferometers, (ii) multi-photon Bragg diffraction between same internal states, and (iii) an about 1000 fold reduction of laser phase noise to -138dBc/Hz. Combining that with a new method to simultaneously stabilize the phases of four frequencies, we achieve 0.2mrad effective phase noise at the location of the atoms. In addition, we use active stabilization to suppress systematic effects due to beam misalignment.

Optical fibers with interferometric path length stability by controlled heating for transmission of optical signals and as components in frequency standards, Holger Müller, Achim Peters, and Claus Braxmaier, *Appl. Phys. B 84,* 401-408 (2006).

We present a simple method to stabilize the optical path length of an optical fiber to an accuracy of about 1/100 of the laser wavelength. We study the dynamic response of the path length to modulation of an electrically conductive heater layer of the fiber. The path length is measured against the laser wavelength by use of the Pound-Drever-Hall method; negative feedback is applied via the heater. We apply the method in the context of a cryogenic resonator frequency standard.

Phase-Locked, High-Power, Low-Noise, Frequency Agile, Continuous-Wave Titanium:Sapphire Lasers, Holger Müller, Sheng-wey Chiow, Quan Long, and Steven Chu, Opt. Lett. **31,** 202 (2006).

The ability to precisely stabilize and manipulate the frequency and phase of laser light is at the basis of the tremendous recent progress in precision measurements, including the realization of optical clocks and tests of fundamental laws of physics. High-precision atom interferometers arguably present the most demanding requirements on the relative phase stability of lasers: Laser light serves as a reference for measuring the phase of the matter waves; thus, lasers with ultra-low phase noise are required for satisfying present accuracy goals of parts per billion or better. To achieve low phase noise, fast feedback mechanisms are necessary to efficiently remove the frequency or phase fluctuations of the laser emission.

We demonstrate a continuous-wave phase-locked system of two Titabium:sapphire lasers, each providing more than 1.6W output power at a wavelength of 852 nm, with a phase noise of -138 dBc/Hz at 1MHz from the carrier. This is an improvement of more than 40 dB over the previous work. This has been achieved by adding an ultrafast feedback channel. The residual phase variance about 10^{-8} rad^2 integrated from 1Hz to 10 kHz. This system can change the offset frequency phase-continuously within 200ns with frequency steps up to 4MHz.

Phase shifts in precision atom interferometry due to the dielectric background of cold atoms, E. Sarajlic, A. Wicht, and S. Chu, in preparation (2005)

We consider the systematic errors in precision atom interferometry due to the index of refraction of cold background atoms. This dielectric background contributes in two-ways: it modifies the amount of momentum transferred in the light-atom interaction and changes the effective wavevector of the optical fields inside the atom cloud. We consider the experimental parameters relevant to our measurement of the fine structure constant, as the experimental limit on the size of this effect is the leading contribution to the systematic uncertainty of -9.7±14ppb.

We use density matrix simulations to determine the evolution of both the interferometer atoms and the cold dielectric background during the interaction with light pulses. We are currently modifying our simulations to address the previously neglected effect of interferometer beam polarization impurity on the background index of refraction. Even on a small level, this effect can increase the index of refraction systematic by redistributing atomic populations out of states that are normally dark to the correct light polarization.

Active sub-Rayleigh alignment of parallel or antiparallel laser beams, Holger Müller, Sheng-wey Chiow, Quan Long, Christoph Vo, and Steven Chu, Optics Lett. **30,** 3323 (2005).

In atom interferometers that use two-photon transitions driven by counterpropagating laser pulses as beam splitters, the phase of the matter waves is measured against the "effective wavevector", i.e, the sum of the wavevectors of two counterpropagating laser beams. Thus, the effective wavevector is affected by errors in the alignment of the beams. Presently, errors of about 50 microradians arise due to the mechanical instability of conventional optics setups. This limits the accuracy of atom interferometers to a few parts per billion (ppb). Moreover, the Rayleigh limit sets a theoretical limit of about 30 microradian on how well a tiny relative misalignment can be resolved by conventional methods. In order to remove this error, we developed an active control system to stabilize the alignment of laser beams, based on comparing the phases of radio frequency beat notes on a quadrant photodetector. This method is neither limited by the Rayleigh criterion, nor by vibrations and creep in optics. It uses an intereference between the beams to measure the angle, rather than an interaction of the beams with the mechanical setup. It reaches an absolute accuracy of 2 microradians for parallel beams and 5 microradians for antiparallel beams, respectively. This is well below the Rayleigh criterion. Angular missalignment is thus no longer an issue in atom interferometry, even at accuracy levels of better than 0.1ppb in the measurement of h/m.

Phase shifts in precision atom interferometry due to the localization of atoms and optical fields, A. Wicht, E. Sarajlic, J. M. Hensley, and S. Chu, Phys. Rev. A, **72:2**, p.23602-1-15 (2005).

Understanding the amount of momentum transferred to an atom in an interaction with light is critical to precision atom interferometer experiments. The basic analysis of interferometer phase shifts models atoms and optical fields as plane waves, neglecting effects arising from their finite spatial extent. In this work we study the momentum transfer in an interaction between localized atoms and localized optical fields. We show the momentum transferred to an atom is given by the local phase gradient of the optical field. We estimate systematic errors due to optical wavefront curvature, beam misalignment and Guoy phase shift in our interferometer, which measured the recoil velocity of a Cesium atom to determine the fine structure constant. These systematic errors were found to be less than 1ppb in recoil velocity, and do not limit the current accuracy of the experiment. However, these effects will be important for future generations of atom interferometer experiments aimed at determining the fine structure constant with sub-ppb accuracy, as well as other precision atom interferometry experiments.

The creation of new states of matter

Probing Pair Correlation in Rotating Bose Gasses in the Fractional Quantum Hall Regime. Edina Sarajlic, Nathan Gemelke, Steven Chu, in preparation.

We report first results probing two-body correlation in the centrifugal limit of small, rotating Bose gases. An ensemble of such gases is prepared in an optical lattice with locally rotating lattice site potentials. An adiabatic pathway was designed and implemented to evolve nonrotating ground states to correlated higher angular momentum states by applying a controlled quadrupole deformation of the rotating potential. These states are analogous to those seen in the fractional quantum Hall effect in two-dimensional electron gases. Pair correlation is probed with single-color photoassociation. In the centrifugal limit, where the trap rotates near its vibration frequency, a reduction is observed in photoassociation rate. Implications of the result are discussed.

Measurement of the Dipole Moment for Bound-bound Transitions of Rubidium Molecules. Nathan Gemelke, Edina Sarajlic, Steven Chu, in preparation.

We report a measurement of the transition strength of optical transitions with deeply bound rubidium molecules, using two-color coherent photoassociation spectroscopy. These transitions have strongest Franck-Condon overlap with the electronic excited states of the molecules, and are most promising for direct detection of molecular populations in photoassociated condensed gases. We describe how direct measurement of two-body correlation in a gas may be achieved by back-action on the bound-bound component of the field applied in coherent two-color photoassociation.

Modulation and Stablization of a Sideband-injected Diode Laser, Nate Gemelke, Edina Sarajlic, Holger Müller, Sheng-wey Chiow, Quan Long, Steven Chu, *manuscript in preparation.*

We describe a method for generating stable, frequency-offset light by current-modulating a laser diode and injection-locking the frequency modulation sideband to a reference frequency. By feeding back a direct current proportional to the laser intensity at the sideband frequency, injection-locking may be maintained over sideband frequencies 0.5-9.5 GHz, and an injection bandwidth which exceeds the sideband frequency. Alternatively, the output radiation is detected and the current adjusted such that the phase of the component at the modulation frequency vanishes. Modulation of the microwave sideband phase is transferred to the light, providing an economical source of phase-modulated light with parasitic amplitude modulation below 1ppt for a modulation index of 2.

Diode-Laser Based Photoassociative Spectroscopy of Rubidium, Nate Gemelke, Edina Sarajlic, Steven Chu, *manuscript in preparation.*

We describe an apparatus for one- and two-color photoassociative spectroscopy of Bose-condensed rubidium. By direct referencing to well-known transitions in polarization spectroscopy of thermally excited iodine molecules, we determine the locations of the $O_g^- \rightarrow |1,-1\rangle + |1,-1\rangle$ and $|2,2\rangle + |2,2\rangle \rightarrow O_g^-, v = 1, J = 0,2$ free-bound transition of rubidium to 12MHz (where the kets give the F and m quantum numbers). A laser locked to this transition is provided by a sideband-injected diode laser, which is then locked to an iodine cell. A second laser is phase-locked to the first at the bound-bound photoassociative transition with the largest Franck-Condon overlap.

Toward realization of a quantum-hall-like array of rotating bosonic clusters, Yannick Bidel, Edina Sarajlic, Seokchan Hong, Nathan Gemelke, Steven Chu, Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society conference, May 17-21, 2005.

We present results on an experiment designed to reach the fractional quantum Hall regime with an ensemble of small clusters of neutral atoms. We demonstrate the ability to produce an optical lattice potential whose sites rotate their principle vibration axes near the resonant frequency, and an ability to impart coherent motion to atoms adiabatically loaded from a Bose-Einstein condensate. We demonstrate the necessary precision in control of the optical lattice and atomic density to study correlation in these systems. We report shifts in the resonant frequencies for exciting rotational motion as the condensate is diluted, an important consequence of few-body physics not previously explored, and a crucial signature for feasibility of quantum-hall type experiments.

Parametric amplification of matter waves in periodically translated optical lattices, Nathan Gemelke, Edina Sarajlic, Yannick Bidel, Seokchan Hong, Steven Chu, Phys. Rev. Lett. **95**, 170404 (2005).

We discovered a method of manipulating Bose-Einstein condensates with time-dependent optical lattice potentials to transfer atoms pairwise into opposing momentum classes. The effect was attributed to shaping of atomic band structure, and is analogous to methods used in nonlinear optics with light. We believe the method may be a viable source for correlated atoms for use in atom interferometry and quantum computation schemes, and are currently devising a method to test for correlation.

These results were presented at the meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society conference, May 17-21.

Precision Feshbach spectroscopy of ultracold Cs_2, Cheng Chin, Vladan Vuletic, Andrew J. Kerman, Steven Chu, Eite Tiesinga, Paul J. Leo, and Carl J. Williams, Phys. Rev. A **70**, 032701 (2004).

Further investigation into Feshbach resonances revealed multiple extremely weak resonances in collisions of ground-state cesium atoms, in addition to the ones already discovered by us (see above). They are associated with g-wave molecular states. In total, more than 60 resonances were detected through variations in the radiative collision cross sections. This allowed us to determine interactions between the atoms, and the molecular energy structure near the dissociation continuum, with unprecedented precision. This not only represented a very successful collaboration of experimental and theoretical efforts, but also provided essential information for cesium Bose-Einstein condensation, cesium molecules, and atomic clock experiments.

Polymer dynamics with single molecules

Effect of Hydrodynamic Interactions on DNA Dynamics in Extensional Flow: Simulation and Single Molecule Experiment, Schroeder, C. M.; Shaqfeh, E. S. G.; Chu, S., Macromolecules **37**, 9242-9256 (2004).

This work is a comprehensive theoretical and experimental study of the effects of intramolecular hydrodynamic interactions (HI) on polymer dynamics in extensional flow. Specifically, we utilize a combination of single molecule DNA experiments and Brownian dynamics (BD) simulations to probe the role of HI for DNA molecules ranging in contour length from 150 to 1300 μm. Quantitative agreement between ensemble-averaged transient molecular extension for experiment and simulation for DNA with 150 μm contour length is shown. We also provide theoretical insight into polymer conformation hysteresis, a phenomenon originally predicted 30 years ago by P. G. de Gennes and experimentally observed by our laboratory for the first time (Schroeder *et al.*, Science, **301**, 1515-1519 (2003)). For DNA chains with contour lengths around 1300 μm, BD simulations show conformation hysteresis. Furthermore, conformation-dependent resistivities are extracted from BD simulations and are utilized in coarse-grained Brownian dumbbell models. Finally, we calculate effective polymer conformational energies in extensional flow and demonstrate that hysteresis results from kinetically-trapped conformational states, as the effective energy landscape exhibits a double-welled potential near the coil-stretch transition for large DNA chains.

Shear Thinning and Tumbling Dynamics of Single Polymers in the Flow-Gradient Plane, Rodrigo E. Teixeira, Hazen P. Babcock, Eric S.G. Shaqfeh and Steven Chu, Marcomolecules, 38(2) 581-592 (2005).
We have directly visualized the conformational changes imparted on single, flexible DNA polymers by a steady, simple shear flow in the flow-gradient plane. Two fluorescently stained DNA double-strand sizes of 22 μm and 80 μm in contour length were employed, and *Wi* values of up to 584 were probed (*Wi* = shear rate × longest polymer relaxation time). By exploitation of the linear proportionality between polymer density and its recorded image, the accessible radius of gyration tensor elements (G_{ij}) were measured. Of those, the ensemble-averaged $<G_{22}>$ and $<G_{12}>$ were related to the bulk shear viscosity and first normal stress coefficient, respectively, via the Giesekus stress tensor. We found their respective behaviors to follow power-law decays of $Wi^{-0.52}$ and $Wi^{-1.28}$ at large *Wi*. Polymer dynamics were also investigated. Like rigid ellipsoids of revolution, polymers displayed a constant partition between positive and negative orientations irrespective of shear rate at *Wi* »1. Unlike them, however, polymers preferred positive orientations, spending there ~ 75% or their time vs 50% for rigid ellipsoids. End-over-end tumbling was observed, confirming a long-standing prediction and numerous single-chain computer simulation studies. The tumbling frequency followed $Wi^{0.62}$, and an equation was derived from simple advection and diffusion arguments to reproduce these observations

Characteristic Periodic Motion of Polymers in Shear Flow, Charles M. Schroeder, Rodrigo E. Teixeira, Eric S. G. Shaqfeh, and Steven Chu, Phys. Rev. Lett. **95**, 018301 (2005)

We have designed a novel shear flow device for single molecule experiments of DNA in the flow-gradient plane of simple shear flow. This device allows for direct observation of the tumbling dynamics of polymers in flow. We show for the first time unambiguous evidence of periodicity in tumbling supported by polymer microstructural experimental data obtained using the flow-gradient device, complemented by results from Brownian dynamics simulations of DNA. The motion of both free and tethered polymer molecules as well as rigid Brownian rods in unbound shear flow is found to be characterized by a clear periodicity or tumbling frequency. Periodicity is shown using a combination of single molecule DNA experiments and computer simulations. In all cases, we develop scaling laws for this behavior and demonstrate that the frequency of characteristic periodic motion scales sublinearly with flow rate.

Dynamics of DNA in the Flow-Gradient Plane of Shear Flow: Observations and Simulations, C. M. Schroeder, R. E. Teixeira, Eric S. G. Shaqfeh, and S. Chu, *Macromolecules*, **38**, 1967-1978 (2005).

We elucidate the dynamical behavior of DNA in steady shear flow using Brownian dynamics (BD) simulations to directly complement recent single molecule DNA experiments (Teixeira et al., *Macromolecules*, **38**, 581-592 (2005)). Observations of DNA motion in the flow-gradient plane of shear flow using a novel flow apparatus allow for measurement of the gradient-direction polymer thickness (δ_2), a microscopic conformational property that has direct influence on macroscopic polymer solution properties. In direct comparison to experiment, we present BD simulation results for lambda-phage DNA (22 μm in length) and 84 μm DNA in terms of both free-draining bead-spring models and models including both intramolecular hydrodynamic interactions (HI) and excluded volume (EV) interactions. Good agreement between experiments and BD simulations is obtained for ensemble averaged measurements of polymer extension, δ_2, and orientation angle over a wide range of flow strengths. Macroscopic solution properties, including the polymer contribution to the shear viscosity and first normal stress coefficient, are calculated.

Single molecule studies of polymer brushes, W.T. Juan and S. Chu, *to be submitted.*

We have developed a technique to construct DNA brushes by immobilizing multiple λ-DNA labeled streptavidin coated beads on the substrate. We have achieved a grafting density of 25 DNA/R_g^2. The entropic driven DNA swelling is demonstrated. Taking advantage of the excellent spatial resolution of the confocal microscope, the parabolic monomer density profile along the swelling direction of the polymer brush, which was proposed by S.T. Milner in 1988, has been demonstrated.
End-tethering few dye labeled DNA molecules into the unstained brush coated substrate, the dynamics of the polymer brush at single molecule level was studied for the first time. At the single molecule level, in addition to the high frequency thermal motion around the DNA backbone, longer time scale collective modes, which were first proposed by de Gennes in 1987, were also observed. The escape of a swelling molecule from the brush region to the random coil state in the buffer region was also monitored.
The responses of an individual molecule of the polymer brush to the shear stress were studied based on the DNA brushes we constructed. The inhomogeneous bending of the swelling molecule under constant shear flow was found. When the shear flow released, multiple relaxation time scales were also observed. It might be due to the high entanglement of molecules in the brush region.

The individualistic dynamics of entangled DNA in solution, Teixeira RE, Dambal AK, Richter DH, Shaqfeh ESG, Chu S, Macromolecules **40**: 2461-2476 (2007)

We present the direct visualizations of single, entangled DNA polymers in three flow experiments: relaxation following a rapid shear deformation, steady shear, and startup shear. To evaluate molecular theories, "test" chains were stained against a background of unstained but otherwise identical chains. To provide a direct link to bulk viscoelasticity, identical preparations were also extensively characterized via mechanical rheometry. The four concentrations studied displayed similar rheological features to synthetic polymers at comparable concentrations and were accordingly classified from semidilute to well-entangled. In entangled solutions, we uncovered two distinct relaxation time scales, with the fast, chain retraction characteristic time, tau(fast) approximate to 10-fold longer than the rotational Rouse time assumed by theoretical models. We also found a high degree of molecular individualism and broad conformational distributions in all experiments at shear rates (gamma) over dot > tau(-1)(fast). This new evidence restricts the applicability of the pre-averaging approximation underlying all closed-form theories developed to date and explains some of the complications in modeling nonlinear flows.

Biological Physics

Optical bonding using silica nanoparticle sol-gel chemistry, Sivasankar S, Chu S, Nano Lett., **7**, 3031-3034

A simple method is described to bond optical components using silica nanoparticle sol-gel chemistry. The silica nanoparticles polymerize into highly branched networks that link the surfaces together. The nanoparticle mediated bonding has several advantages to currently used optical joining technologies. The bonding is a room temperature process and does not require any clean room facilities. The bonded interface has a high mechanical strength and low scattering. The bonding is resistant to organic solvents on silylation with hydrophobic surface groups. This method achieves 100% successful bonding rates between soda lime glass slides. The bond-setting time and be can tailored to allow time for precision optical alignment.

The role of fluctuations in tRNA selection by the ribosome, T.H. Lee, S.C. Blanchard, H.D. Kim, J.D. Puglisi, and S. Chu, Proc. Nat. Acad. Sci. **104**,13661-5 (2007).

This work is an extension of our previous single molecule studies of ribosome. The detailed mechanism of how the ribosome decodes protein sequence information with an abnormally high accuracy, after forty years of study, remains elusive. A critical element in selecting correct tRNA transferring correct amino acid is "induced fit" between the ribosome and tRNA. Using single molecule methods, the induced fit mechanism is shown to favorably position the correct tRNA after initial codon recognition. We provide evidence that this difference in positioning and thermal fluctuations constitutes the *primary* mechanism for the initial selection of tRNA. This work demonstrates thermal fluctuations playing a critical role in the substrate selection by an enzyme.

Fluctuations of tRNAs between classical and hybrid states, Harold D. Kim, Joseph D. Puglisi, and Steven Chu, Biophys J. 2007 Aug 10

Adjacent tRNAs in the A and P sites of the ribosome are in dynamic equilibrium between two different conformations called classical and hybrid states before translocation. Here, we have used single-molecule Fluorescence Resonance Energy Transfer (sm-FRET) to study the effect of Mg^{2+} on tRNA dynamics with and without an acetyl group on the A site tRNA. When the A-site tRNA is not acetylated, tRNA dynamics do not depend on [Mg^{2+}], indicating that the relative positions of the substrates for peptide bond formation are not affected by Mg^{2+}. In sharp contrast, when the A-site tRNA is acetylated, Mg^{2+} lengthens the lifetime of the classical state but does not change the lifetime of the hybrid state. Based on these findings, the classical state resembles a state with direct stabilization of tertiary structure by Mg^{2+} ions whereas the hybrid state resembles a state with little Mg^{2+}-assisted stabilization. The antibiotic viomycin, a translocation inhibitor, suppresses tRNA dynamics, suggesting that the enhanced fluctuations of tRNAs after peptide bond formation drives spontaneous attempts at translocation by the ribosome

IV. Talks

There have been many (>40/year) public talks, named lectures, plenary, invited and contributed talks given by during the grant period given by the P.I.

A sampling of conference contributions of students and post doctoral fellows:

Bianxiao Cui, One at a time, live tracking of nerve growth factor transport in axons, Gordon Research Conference on Neurotrophic factors, Newport, (2007)

Bianxiao Cui, Temperature dependence of the nerve growth factor transport in neurons, Biophysical Society Meeting (BPS), Baltimore (2007)

H. Müller, High-precision, large area atom interferometry to determine the fine-structure constant and to test quantum electrodynamics, Quantum Engineering based on Atoms and Photons Meeting, February 26th - March 2nd, Hannover, Germany, 2007.

H. Müller, High-precision, large area atom interferometry to determine the fine-structure constant and to test quantum electrodynamics., Universität Hannover, March 07, 2007, Hannover, Germany.

Bianxiao Cui, tracking axonal transport in microfluidic devices, Biophysical Society Meeting (BPS), Salt Lake City, (2006)

Bianxiao Cui, Tracking the axonal transport of nerve growth factor using quantum dot, Frontiers in Live Cell Imaging, NIH, Bethesda, (2006)

H. Müller, A new photon recoil measurement of the fine structure constant, 20th European Frequency and Time Forum, 27-30 March 2006, Braunschweig, Germany (2006).

H. Müller, *A new phton recoil measurement: towards a new determination oif the fine-structuire constant.* 20th European Frequency and Time Forum, March 27-30, 2006. Braunschweig, Germany.

Bianxiao Cui, microfluidic neuronal network, Biophysical Society Meeting, Long Beach, (2005)

C. Vo, H. Müller, S.-w. Chiow, Q. Long, and S. Chu, Measuring h/Mcs using atom interferometry for a determination of the fine structure constant alpha. Atomic Clock Ensemble in Space Workshop 219095 (2005).

Sheng-wey Chiow, Holger Müller, Quan Long, Christoph Vo, and Steven Chu, A new photon recoil measurement towards determining the fine structure constant, Gordon Research Conference on Atomic Physics, Tilton, New Hampshire, June 26-July 1, 2005.

Sheng-wey Chiow, Holger Müller, Quan Long, Christoph Vo, and Steven Chu, A new photon recoil measurement towards determining the fine structure constant, Stanford Photonics Research Center Annual Symposium, Stanford, CA, September 19-21, 2005

Holger Müller, Sheng-wey Chiow, Christoph Vo, and Steven Chu, A new photon recoil measurement to determine the fine-structure constant, spring meeting of the German Physical Society (DPG), Berlin (2005).

Christoph Vo, Sheng-wey Chiow, Holger Müller, and Steven Chu, A new photon recoil measurement to determine the fine-structure constant, Poster, spring meeting of the German Physical Society (DPG), Berlin (2005).

Holger Müller, Tests of Lorentz invariance using hydrogen molecules, spring meeting of the German Physical Society (DPG), Berlin (2005).

Holger Müller, Tests of Lorentz invariance using vacuum and matter filled cavities, spring meeting of the German Physical Society (DPG), Berlin (2005).

N. Gemelke, E. Sarajlic, Y. Bidel, S. Hong, S. Chu, *Period-doubling Instability of a Bose-Einstein Condensate in a Vibrated Optical Lattice.* Meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society conference, May 17-21, 2005.

N. Gemelke, Y. Bidel, S. Hong, E. Sarajlic, S. Chu, *Experimental Progress Toward a Quantum Hall Array of Bosonic Atoms.* Meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society conference, May 17-21, 2005.

Holger Müller, Sheng-wey Chiow, Christoph Vo, and Steven Chu, *A new photon recoil measurement to determine the fine-structure constant α,* Main Talk at the Annual Meeting of the German Physical Society, Berlin, Germany 2005.

Christoph Vo, Sheng-wey Chiow, Holger Müller, and Steven Chu, *A new photon recoil measurement to determine the fine-structure constant α,* Poster at the Annual meeting of the German Physical Society, Berlin, Germany 2005.

Sheng-wey Chiow, Holger Müller, Quan Long, Christoph Vo, and Steven Chu, *A new photon recoil measurement towards determining the fine structure constant,* Gordon Research Conference on Atomic Physics, Tilton, New Hampshire, June 26-July 1, 2005